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Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes

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Abstract

Background, Aims and Scope. Huge amounts of sewage sludge, that need to be handled, are generated all around the world from wastewater treatment plants and its management in an economically and environmentally acceptable way has become a matter of increasing importance during the last few years.
In this paper, we make use of Life Cycle Assessment (LCA) to compare biological and thermal processes, that is to say, anaerobic digestion versus pyrolysis and incineration. This paper will complete the analysis performed in a wastewater treatment plant, where sludge post-treatment was identified as one of the main contributors to the environmental impact on the global system.

Methods. LCA is a tool for evaluating the environmental performance of goods as well as processes or services (collectively termed products). ISO 14040 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a system throughout its life cycle: from the production of raw materials to the disposal of the waste generated. In this study, data relating to the actual scenario from an existent wastewater treatment plant were considered. Both bibliographical and real data from existing facilities were used for the thermal processes proposed.
The Centre of Environmental Science (CML) of Leiden University's methodology was chosen to quantify the potential environmental impacts associated with the different scenarios under study. The software SimaPro 5.1 was used and CML factors (updated in 2002) were chosen for characterisation and normalisation stages.

Results and Discussion. In a previous study, sewage sludge was found to be a critical point in the environmental performance of a wastewater treatment plant, so different alternatives have been tackled here. Anaerobic digestion followed by land application of pasty sludge comprises both energy recovery and nutrient recovery. Other thermal processes, such as incineration or pyrolysis, allow energy recovery (both electrical and thermal) and, although nutrients are lost, new co-products are produced (tar and char at pyrolysis).
Here, the most adverse case (that is to say, the total amount of heavy metals is supposed to be released from the sludge and reach the environment) was applied to consider the most negative impact due to sludge spreading in agricultural soils; so more research is required in order to establish the precise amount of heavy metals that is effectively uptaken by the plants and crops as well as the amount that is transferred to another phase as a leachate. Thermal processes are presented here as a good option to recover energy from the sludge; although the value of nutrients is lost. Tar and char, co-products from pyrolysis, are good examples that were evaluated here, recycling of bottom ashes from sludge incineration or manufacture of ceramic materials from sludge are other options to be studied in the near future.

Conclusion. During the last few years, several opinions have been declared in favour of land application, incineration or pyrolysis, but many voices have also spoken out against each one. To obtain general conclusions for an overall comparison of different post-treatment of urban wastewater sludge is not easy as there are many contradictory aspects. The most effective utilisation of sewage sludge implies both energy and material reuse, but this is not always possible. Nevertheless, we think that land application of digested sludge is an acceptable option, probably not the best but at least a good one, for sludge treatment as long as efforts are focused on the minimisation of heavy metal content in the final cake.

Keywords: Anaerobic digestion; incineration; pyrolysis; sewage sludge; sludge treatment processes; urban wastewater treatments; wastewater

Introduction

The management of sewage sludge in an economically and environmentally acceptable way is a matter of increasing importance. The stricter regulations on sludge disposal in both industrialised and emerging countries are going through significant, prompt and continuous changes.

At this moment, the European legislation applicable to sludge is evolving rapidly [1]. In particular, a new Directive on sludge has been at the stage of its third draft since April 2000 [2], a new Directive on incineration was issued in December 2000 [3] and another document regarding biological treatment of biowaste is being drawn up [4].

Historically, most of the sludge generated has been directed to incineration, landfilling or disposed in the sea1. Only a small portion has been reused in agriculture, mainly because of the apprehension that the application of treated sludge to agricultural land may cause the transfer of pathogens, viruses, heavy metals and organochlorine residues to the crops

[1] Disposal of sewage and industrial waste at sea has ceased following the Oslo Convention and Paris Commission (OSPAR 1992). One of the objectives of the Urban Wastewater Treatment Directive (1991) was the phasing out of sewage sludge disposal at sea by December 1998.

and/or animals, with potential transport up the food chain to humans. In this sense, anaerobic digestion cannot provide a 100% reduction of pathogens and viruses, while a thermal drying technology, consisting on gasification and combustion with recovery of energy, can effectively attain that [5]. Furthermore, a study from the late seventies regarding new technologies reported the advantages of sludge pyrolysis over sludge incineration or landfill, such as less air and no fuel consumption or less transport requirements [6].

Life Cycle Assessment (LCA) is a tool for evaluating the environmental performance not only of goods, but also of processes or services (collectively termed products). ISO 14040 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a system throughout its Life Cycle [7]. This practice is obtained by means of a systematic, four-step procedure: goal and scope definition, inventory analysis, impact assessment and interpretation.

Since its early stages, the first studies to look at life cycle aspects of products date from the late sixties and early seventies, and focused on issues such as energy efficiency, the consumption of raw materials and, to some extent, waste disposal [8], LCA has proven to be a valuable tool to verify and analyse environmental considerations of goods and service systems that need to be part of the decision-making process towards sustainability [9].

The application of LCA to sludge management has turned out to be quite extensive. Bridle and Skrypski-Mantele [5] reported qualitative conclusions on sludge management by means of four criteria based on a sustainable life-cycle approach. Hwang and Hanaki [10] exclusively quantified the amount of CO_2 produced from the construction, operation and dismantlement of a sewage sludge treatment system, in order to estimate its global warming potential. Suh and Rousseaux [11] carried out a comparison of five alternative scenarios, but the only results from their relative environmental profile (with no absolute numbers) were presented. A more detailed analysis was performed by Houillon and Jolliet [12] inside the framework of the Ecosludge project. Six scenarios were compared but, as in this first paper of the study only energy and emissions contributing to global warming were quantified, no final conclusions on their global environmental impact could be obtained. Finally, Lundin et al. [13] have gone further and performed an environmental and economic analysis of four options, including agricultural application, co-incineration with waste and two recent technological approaches for phosphorus recovery (Bio-Con and Cambi-KREPPO). While the former two proved to have environmental or economical restrictions, the latter two turned out to be a promising solution for sewage sludge treatment.

The general aim of this work is to complete the analysis performed at a wastewater treatment plant (now referred to as WWTP) [14], where sludge post-treatment was identified as one of the main contributors to the environmental performance of the global system. To achieve this target, several options will be compared with the actual post-treatment of the sludge generated in the wastewater plant mentioned considering a broad number of impact categories, which will provide a comprehensive knowledge of the environmental performance of the process under study.

1 Goal and Scope Definition

1.1 Objectives

The goal of this assessment is to examine different alternatives of sewage sludge post-treatment in order to quantify and compare the potential environmental performance of three different types of post-treatment systems: agricultural use, incineration and pyrolysis.

1.2 Functional unit

The functional unit (FU) is the unit of comparison in a Life Cycle Inventory (LCI). Traditionally, LCI studies have been related to goods and their FU have been expressed in terms of the system output; however, the FU of a waste management system is not directly related to the manufacture of a certain product, but to the management of the waste; consequently, the FU may be defined in terms of the system input, i.e. the waste to be managed [15]. Accordingly, the management of 1 ton of thickened mixed sludge in dry basis (1 tDM) was chosen.

1.3 System boundaries assumption

McDougall et al. [15] pointed out different possible approaches to define the system boundaries: vertical and horizontal analysis. Bearing in mind both approaches, comparisons between several scenarios are better when considering the horizontal approach. In this case, the study was focused on the assessment of the environmental burdens of the waste, once produced. Therefore, the system boundaries of the study were established as the following:

a) The construction of different sludge post-treatment facilities, including machinery and electric installation, was not considered and only the operation stage was taken into account for the analysis.
b) The operation of the wastewater treatment plant was not considered since it is shared by all the scenarios, as the thickened mixed sludge was selected as the starting point of our study.
c) The scenarios considered comprised several stages: conditioning (mechanical dewatering and/or thermal drying), post-treatment (incineration, pyrolysis or landfill) as well as intermediate activities such as transport.

Fig. 1 displays a block diagram of the different scenarios. The existing scenario corresponds to a Galician WWTP that deals daily with more than 3.2 tons of sludge (dry matter). The others are hypothetical situations for alternative post-treatments.

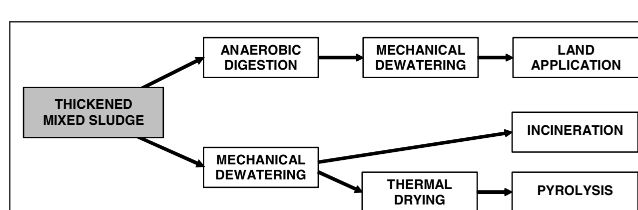

Fig. 1: A block diagram of the different scenarios of sludge management

1.4 Data quality and simplifications

To carry out the inventory, data were collected mainly from existing facilities, either directly by fieldwork or by bibliographical sources. A few estimations had to be made due to the lack of more accurate data.

As far as electricity consumption is concerned, an electrical percentage distribution according to data from the Institute for Diversification and Saving of Energy was used [16]. Although, some data for the environmental burdens of electricity production in Spain were derived from a major EU funded research project called ExternE [17], their high uncertainty only allows their use as background information. Consequently, information from the IDEMAT, a well-known database, was selected [18].

In fact, the IDEMAT database was handled for all the upstream productions. The exceptions were chemical manufacture [19,20] and charcoal production [21].

Regarding the polymer used during mechanical dewatering, data from polyacrylamide production was considered by means of acrylonitrile fabrication, one of the raw materials used in acrylamide manufacture [22].

1.5 Substitutions

Quantification of the products and energies avoided is required in order to compare the scenarios proposed. With this aim, the following calculations were made:

a) Fertilisers avoided: The fertilising value of the sludge when applied to agricultural land was determined based on the Nitrogen (N) and Phosphorus (P) content and the availability of these nutrients according to Bengtsson et al. [23]. As industrial products avoided, N-based and P-based fertilisers were chosen [18].
b) Activated carbon avoided: As described below, the char from pyrolysis can be used as a raw material for activated carbon manufacture. As a consequence, industrial charcoal production was considered [21].
c) Fuel avoided: As tar can be used as a fuel, the production of crude oil avoided was included [18].
d) Energy avoided: Both in incineration and pyrolysis, heat is recovered from flue gas and used for internal purposes. At the incineration plant, surplus energy is exported to the district heating system and permits the saving of gas. As a result, the production avoided of thermal energy with gas was associated [21]. As no specific information was provided, the same situation was supposed at the pyrolysis facility.

2 Life Cycle Inventory

An LCI analysis is concerned with the data collection and the calculation procedures necessary to complete the inventory [7].

2.1 Sewage sludge

Sewage sludge is a by-product of the water treatment process. Although three categories of sludge can be recognised [24], the present work was only focused on one of them: the sludge generated in the treatment of urban wastewater. **Fig. 2** exhibits a conventional WWTP as well as the points of sludge generation in the treatment process.

Table 1 shows the typical composition of mixed (MS) and digested sludge (DS). Dry matter (DM) is a very significant parameter, due to its influence on the post-treatment processes. In particular, it has an effect on both fuel requirements and exhaust gas production at the incineration process and the drying at sludge landfill. Volatile matter (VM), a measure of the sludge organic content, is also a key parameter, for example because it defines the heat content, the most important parameter regarding the energetic use of sewage sludge.

Table 1: Composition of mixed and digested sludge

Component	Unit	Mixed Sludge (MS)	Digested Sludge (DS)
Dry Matter (DM)	g/L	10	30
Volatile Matter (VM)	%DM	72	50
C	% VM	51	49
H	% VM	7.4	7.7
O	% VM	33	35
N	% VM	7.1	6.2
S	% VM	1.5	2.1
P	% VM	2	2
Cl	% VM	0.8	0.8
K	% VM	0.3	0.3
Al	% VM	0.2	0.2
Ca	% VM	10	10
Fe	% VM	2	2
Mg	% VM	0.6	0.6

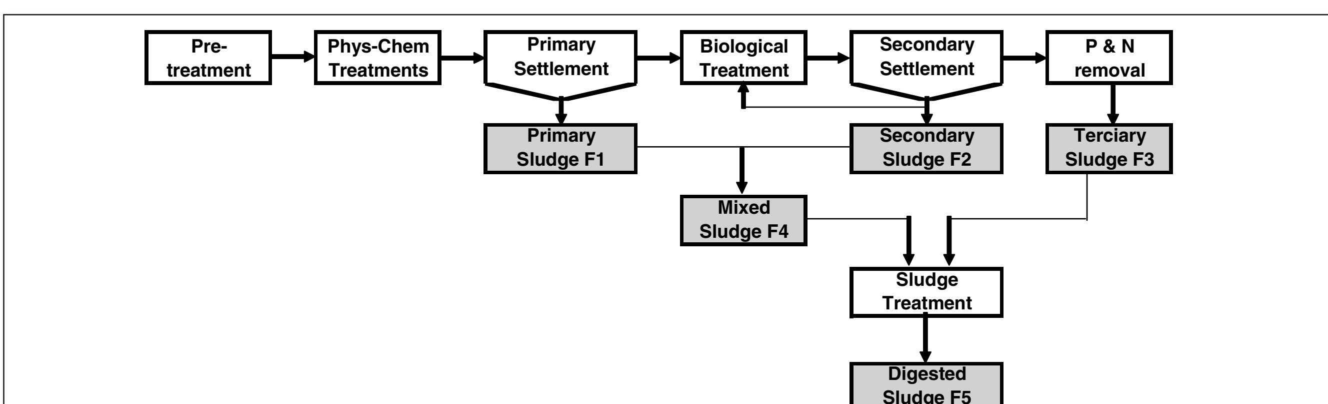

Fig. 2: A conventional wastewater treatment plant and sludge generation [24]

Table 2: Concentrations of heavy metals in sludge used for land (mg/kg dry matter)

	Range in the EU [24]	Limit Values Directive [42]	Limit Values Proposed [2]	WWTP Concentration [14]
Cd	0.4–3.8	20–40	10	1.38 ± 0.35
Cr	16–275	–	1,000	79.12 ± 15.99
Cu	39–641	1,000–1,750	1,000	193.19 ± 43.17
Hg	0.3–3	16–25	10	1.43 ± 0.01
Ni	9–90	300–400	300	29.24 ± 8.80
Pb	13–221	750–1,200	750	334.05 ± 48.37
Zn	142–2,000	2,500–4,000	2,500	1,521 ± 57

Another fundamental factor, when sludge post-treatment is considered, is the metal content. Numerous heavy metals are present in sludge and, generally, at highly variable concentrations depending on the relative contributions of specific industrial wastewaters to the overall flow. **Table 2** displays the average content of heavy metals in the EU Member States, the limit values established and proposed by the European Commission, as well as the results coming from an analytical study of the anaerobically digested sludge from the WWTP during 2001.

2.2 Description and data of actual scenario

Among the three methods of stabilisation normally put into practice in wastewater treatment plants (digestion, lime stabilisation and heat treatment), anaerobic digestion is the most popular procedure within the European Union. This biological sludge decomposition in the absence of oxygen and under controlled conditions by the action of microorganisms aims to produce methane and digested sludge.

Energetically, anaerobic digestion shows advantages, even if the temperature in the digesters must be continuously maintained at 35ºC. The excess of gas can be employed to produce electricity and heat (yields of 36% and 50%, respectively) or burned with a torch at 1,200ºC [25].

At the evaluated plant, almost one third of the total biogas production is used to keep the digester at a suitable temperature, while the excess is totally burned with a torch [14] and therefore no extra benefit is attained from the gas.

Afterwards, this scenario comprises a filter belt where the sludge, previously mixed with a polymer, is fed onto the belt and, as it moves along, water is removed and passes through the weave of the belt. To perform this process and to attain a final dry matter content of 23.7%, different requirements have to be considered: polymer manufacture and its transportation, water and electricity [14].

Until two years ago, sludge cake was fated to two disposal scenarios. Local authorities allowed, as an exceptional and temporary solution, the disposal of sewage sludge at municipal solid waste landfill; moreover, cake sludge was distributed among local farmers for agricultural use as a substitute for chemical fertilisers. However, nowadays, the second alternative is the only possible one and all the local farmers that use sewage sludge are controlled according to Spanish legislation relating to heavy metal contents and other parameters not only regarding the sludge but also the soil after sludge application [26].

Sludge is assumed to be produced all year, but it can only be spread on arable land during spring and autumn; this implies that the products are stocked up during several months. The storage, transport, machinery fuel needed for land application, the fertilisers avoided and the heavy metal emissions to soil were included in the inventory [14].

This real scenario (noted as Scenario 0) is likely to be no longer endorsed because of stakeholder perceptions and increasingly strict environmental regulations. As a result, it needs to be changed into alternative scenarios such as those described below.

Table 3 displays the inventory data handled to evaluate this scenario.

Table 3: Inventory data and database used for Scenario 0 (anaerobic digestion + mechanical dewatering + land application). Values are presented per FU

	Unit	Amount
Anaerobic Digestion		
Electrical consumption	kWh	88.56
Air emission of CO_2 (biogenic)	kg	1,291
Air emission of CO	kg	0.84
Air emission of NO_2	kg	0.85
Air emission of N_2O	kg	0.02
Air emission of particles	kg	0.08
Dewatering (filter belt)		
Electrical consumption	kWh	49.09
Acrylonitrile consumption	kg	5.50
Acrylonitrile transport by truck	t·km[1]	3.99
Sludge transport by truck	t·km	105.48
Land Application		
Electrical consumption	kWh	58.50
Diesel for sludge application	kg	0.73
N-fertiliser avoided	kg	17.87
P-fertiliser avoided	kg	14.32
Air emission of CH_4	kg	3.18
Soil emission of Cr	kg	0.08
Soil emission of Cu	kg	0.19
Soil emission of Pb	kg	0.33
Soil emission of Zn	kg	1.51

NOTE: t·km = Unit for transportation that includes both the amount transported (in t) and the distance (in km)

2.3 Description and data of alternative scenarios

Scenario 1 – Incineration: To date, the prevailing technologies for mono-combustion of sludge are fluidised bed combustors (FBC) and multiple heart furnaces (MHF). Current tendency goes to the FBC configuration, due to mainly its lower extra-fuel consumption and emissions. In fact, this is the configuration existing in the thermal waste treatment plant from which the data come [27].

Almost 2 million tons of municipal sewage sludge (approx. 3.5% DM content) are received in the plant and dewatered by adding an organic coagulating agent and passing them through 22 centrifuges. Then, the resultant, thickened sludge (average DM content of 35%) is thermally treated at 850ºC in three FBC (two of them with 4 ton/h of capacity and the third one with 5.2 ton/h).

An important amount of heavy fuel oil has been used for years as an extra fuel in order to achieve the adequate combustion conditions. Nowadays, this requirement has been decreased and less heavy fuel oil is combined with meat and bone meal as extra fuel. Exhaust gases from the furnaces are used for the production of energy; a large part is used at the incineration plant and the remaining heat is used for heating and the production of warm water via the city district heating.

Solid residues of sludge incineration are generally classified as bottom ashes (if directly kept from the furnace) or fly ashes (if collected in flue gas treatment devices). The former are generally suitable for non-hazardous waste disposal sites but the latter need, on some occasions, a previous stabilisation-solidification process before disposal [28]. However, no special treatment is required in this case: all the solid residues are taken for disposal in Vienna, except for the filter cake (that is to say, the ash residues from the electrostatic precipitator) which is taken to an underground disposal in an abandoned salt mine.

Air pollution control is required for the reduction of emissions and the equipment more often used can be classified in two main groups: units that can separate solid particles and units that reduce gaseous contaminants by absorption, adsorption and/or chemical reaction [28]. At the facilities inventoried, SNCR process for NO_X reduction, electrostatic precipitators, a two-stage wet scrubber system for flue gases, electrodynamic venture scrubbers for fine dust particle separation and activated coke filters ensure continuous compliance with the strict exhaust gas emission values for several pollutants such as carbon monoxide or nitrogen oxides: 229 mg/Nm^3 and 218 mg/Nm^3 as maximum concentrations, respectively.

The inventory data used to study this alternative scenario are presented in **Table 4**.

Table 4: Inventory data and database used for Scenario 1 (mechanical dewatering + incineration of pasty sludge). Values are presented per FU

	Unit	Amount
Sludge transport by train	t·km	286
Dewatering (centrifuge)		
Electrical consumption	kWh	52.5
Acrylonitrile consumption	kg	3.72
Acrylonitrile transport by truck	t·km	2.64
Incineration		
Electrical consumption	kWh	9.50
Heavy fuel oil	kg	31.0
Meat and bone meal	kg	273
NaOH consumption	kg	12.2
Lime consumption	kg	4.96
Ammonia consumption	kg	3.72
Air emission of CO_2 (biogenic)	kg	1,500
Air emission of CO_2	kg	800
Air emission of CO	mg	0.151
Air emission of NO_2	mg	1.00
Air emission of particles	µg	2.00
Air emission of dioxin&furan	ηg	$3{\cdot}10^{-5}$
Combustion waste	kg	273
Filter cake	kg	19.0
Transport of filter cake by truck	t·km	12.2
Heat avoided	kWh	1,747

Scenario 2 – Pyrolysis: Filter press is another dewatering technique, which makes it possible to reach a high dewatering level. To perform this process and to attain a final dry matter content of 30%, requirements include water, polymer manufacture and transportation as well as electricity [29].

Through thermal drying, a further reduction of the water content of the sludge can be achieved. Moreover, the hygienic quality of the sludge is improved and an opportunity of an economic recovery is provided. Several configurations can be chosen for each single case and its specific prevailing conditions have to be considered. In this study, the average data coming from several plants were handled where the evaporated water is condensed and returned to the input flow of the WWTP and the dried sludge granulate can be filled either into silo-trucks or into big bags [30,31].

Data from 8 different facilities were handled in order to quantify the inputs required to carry out this process: thermal and electrical energy, as well as process water. Sulphuric acid and caustic soda are consumed in the bioscrubber to remove the pollutants present in the exhaust gas; although no quantitative data are available. Regarding releases to nature, only volatile organic compounds (VOCs) in air emissions were considered.

Pyrolysis is a thermal decomposition of organic substances in the absence of oxygen at temperatures ranging between 300 and 900ºC [32]. Its products are pyrolysis gas (also named syngas), oil (also called tar) and char, which can be produced at variable amounts and used in different ways. Syngas is generally reused as an internal energy source for the pyrolysis process and, when an extra production takes place, it can be exported out of the system. The tar can be used as fuel, with a high heating value similar to that of crude oil [32]; for this reason, the avoided production of crude oil was included in the analysis. The char can also be burnt as fuel; however its utilisation as raw material for other

Table 5: Inventory data and database used for Scenario 2a (mechanical dewatering + thermal drying + pyrolysis of dried sludge with reutilisation of syngas only) and Scenario 2b (mechanical dewatering + thermal drying + pyrolysis of dried sludge with reutilisation of all the fractions produced). Values are presented per FU

	Unit	Amount
Sludge transport by train	t·km	286
Dewatering (filter press)		
Electrical consumption	kWh	40.0
Acrylonitrile consumption	kg	5.00
Acrylonitrile transport by truck	t·km	3.75
Thermal Drying		
Water consumption	m^3	15.2
Electrical consumption	kWh	118
Heat consumption	kWh	1,638
Air emission of VOC	g	44.3
Pyrolysis		
Electrical consumption	kWh	244
Air emission of CO_2 (biogenic)	kg	579
Air emission of CO	g	480
Air emission of NO_2	g	217
Air emission of N_2O	g	3.66
Air emission of particles	g	43.46
Heat avoided	kWh	4.15
Sc2a: Char	kg	460
Sc2b: Charcoal avoided	kg	230
Sc2a: Tar	kg	40
Sc2b: Crude oil avoided	kg	40

processes such as activated carbon manufacture has been reported as an advantageous way of recycling [33–35]. Here, this option was taken into account and the avoided production of charcoal was considered.

Table 5 shows the inventory data handled to evaluate both options of this scenario.

To summarise, there are three options proposed as alternatives to the real scenario (Sc.0):

- Mechanical dewatering + Incineration of pasty sludge (Sc.1)
- Mechanical dewatering + Thermal drying + Pyrolysis of dried sludge when the syngas is the only product reused for the purpose of energy recovery (Sc.2a)
- Mechanical dewatering + Thermal drying + Pyrolysis of dried sludge when all the fractions produced (syngas, char and tar) are reused in different ways (Sc.2b)

3 Life Cycle Impact Assessment

The LCIA phase aims to examine the system from an environmental perspective using category indicators, derived from the LCI results. The LCIA phase also provides information for the interpretation phase [7].

This stage starts with the classification step, when the emissions and resources are sorted into different groups or impact categories according to their potential impact on the environment. In accordance with a list of impact categories elaborated by Guineé et al. [36], some of them were chosen among the so-called baseline impact categories. Descriptions as well as the characterisation factors used are published on the list of references presented on **Table 6.**

Table 6: Characterisation factor references for each impact category considered

Impact Category	References
Eutrophication (EP)	Heijungs R, Guinée J, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, de Goede HP (1992): Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Science (CML), Leiden University, Leiden
Stratospheric ozone depletion (ODP)	World Meteorological Organisation (1992): Scientific assessment of ozone depletion: 1991. Global Ozone Research and Monitoring Project – Report no. 25, Geneva World Meteorological Organisation (1995): Scientific assessment of ozone depletion: 1994. Global Ozone Research and Monitoring Project – Report no. 37, Geneva World Meteorological Organisation (1999): Scientific assessment of ozone depletion: 1998. Global Ozone Research and Monitoring Project – Report no. 44, Geneva
Global warming (GWP)	Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds) (2001): IPCC Third Assessment Report: Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge
Acidification (AP)	Huijbregts M (1999): Life cycle impact assessment of acidifying and eutrophying air pollutants. Calculation of equivalency factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, Amsterdam
Photo-oxidant formation (POFP)	Derwent RG, Jenkin ME, Saunders SM, Pilling MJ (1998): Photochemical ozone creation potentials for organic compounds in Northwest Europe calculated with a master chemical mechanism. Atmospheric Environment 32: 2429–2441 Jenkin ME, Hayman GD (1999): Photochemical ozone creation potentials for oxygenated volatile organic compounds: sensitivity to variations in kinetic and mechanistic parameters. Atmospheric Environment 33: 1775–1293
Depletion of abiotic resources (ADP)	Guinée JB (ed) (2001): Life Cycle Assessment an operational guide to the ISO standard. Volume I, II, III, Leiden University, Leiden
Human toxicity (HTP)	Huijbregts MAJ (1999): Priority assessment of toxic substances in LCA. Development and application of the multi-media fate, exposure and effect model USES-LCA. IVAM environmental research, University of Amsterdam, The Netherlands Huijbregts MAJ (2000): Priority Assessment of Toxic Substances in the frame of LCA. Time horizon dependency of toxicity potentials calculated with the multi-media fate, exposure and effects model USES-LCA. Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, The Netherlands

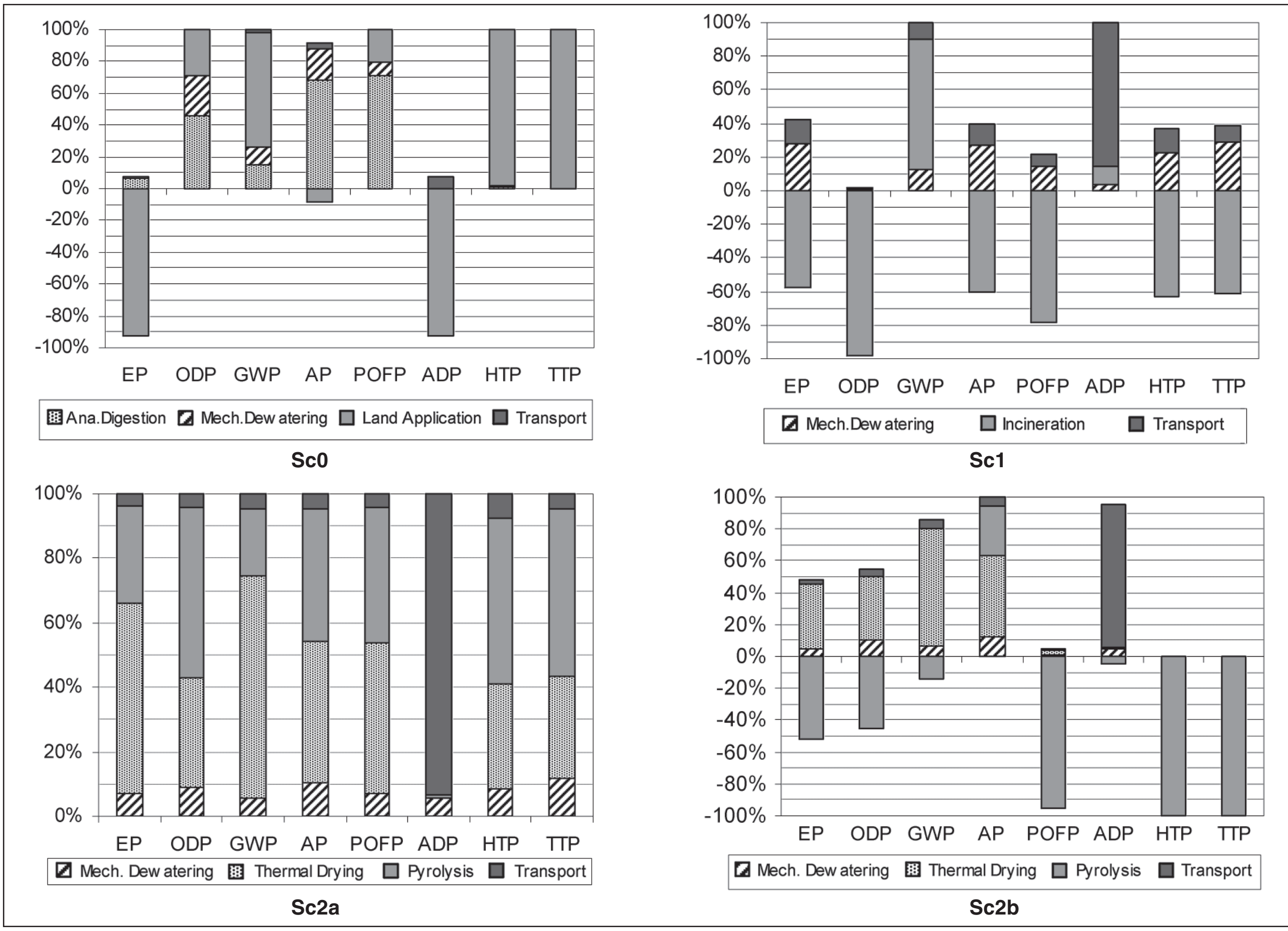

Fig. 3: Characterisation profiles for each scenario. **Sc0** comprises anaerobic digestion + mechanical dewatering + land application; **Sc1** mechanical dewatering + incineration of pasty sludge, **Sc2a** mechanical dewatering + thermal drying + pyrolysis of dried sludge (only syngas is reused) and **Sc2b** mechanical dewatering + thermal drying + pyrolysis of dried sludge (all the fractions produced are reused). See Table 7 for impact category acronyms

Once classification is finished, characterisation takes place in order to quantify the potential contribution of an input or an output to a specific impact, allowing aggregation into a single score in the corresponding impact category. Here, the results are shown in terms of relative contribution of its life cycle steps (subsystems) to the different impact categories (**Fig. 3**). As each impact category is expressed in its corresponding reference unit, results are presented in percentages to display characterisation results with the same figure. For each column, the percentage of 100% stands for the total impact of all subsystems in their corresponding impact category. A negative value means that the environmental impact is reduced due to the production of materials or energy avoided.

ISO 14042 [7] defines normalisation as the calculation of the magnitude of indicator results relative to reference information, which may relate to a given community, person or system, over a given period of time. The main aim of this step is to better understand the relative importance and magnitude of characterisation results. The normalisation factors used here were selected taking the situation in West Europe as a reference for all impact categories and the reference information used refers to 1995, the most recent list available [37]. Comparative results are displayed in **Fig. 4**, where ADP, ODP

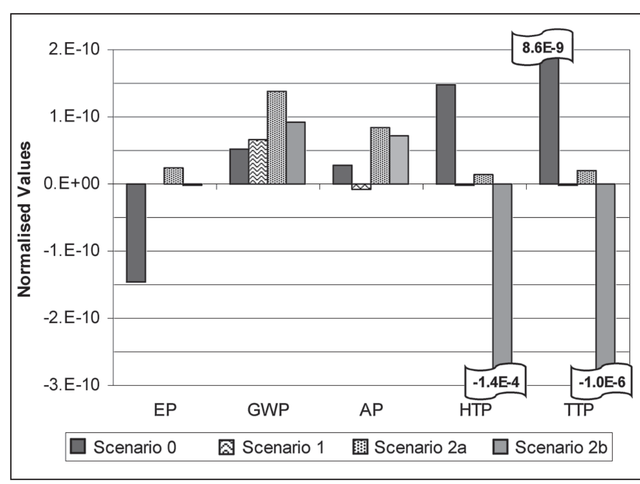

Fig. 4: Normalisation results for each impact category considered in this work

and POFP were eliminated, as their values are not significant in comparison to the other categories presented.

It is generally recognised that the weighting element in LCIA requires political, ideological and/or ethical values, so a high degree of subjectivity is always involved, for this reason this stage was left out of this study.

4 Life Cycle Interpretation

Quantitative analysis of contributors to the environmental impact in each scenario. Life Cycle Interpretation is a systematic technique to identify, qualify, check and evaluate information from the results of the LCI analysis and/or LCIA of a system, and present them in order to meet the requirements of the application as described in the goal and scope of the study [7].

From Fig. 3, scenarios 0, 1 and 2b entail both disadvantageous (positive values of environmental impact) and beneficial consequences (negative values) on the environment. The former are due to the emissions and resources, consumption associated to each process while the latter are due to the savings of other product manufacture. On the one hand, anaerobic digestion followed by land application of pasty sludge entails nutrient recovery by means of the application of the sludge to the soil, bearing in mind the adequate dose according to legislation. On the other hand, the other options proposed allow energy recovery (both electrical and thermal) and, although nutrient benefits are lost, new co-products are produced (such as tar and char at pyrolysis) that can be used to substitute other products.

Considering the overall impact on the environment, the main contributor is specifically the post-treatment step, that is to say, land application, incineration or pyrolysis, while both transport and pre-conditioning activities entail a minor consequence on the environmental impact of the whole scenario (with the exception of ADP for scenarios 1 and 2). Thermal drying is an exception, being the major contributor in four of the eight impact categories studied at scenario 2a; the reason behind this important contribution is the high consumption of energy (both electrical and thermal) required to carry out the drying and achieve the dryness requirement (90%) to perform the pyrolysis with no extra fuel.

Quantitative comparison of the environmental performance for all the scenarios. In Fig. 4, a comparison of all scenarios is presented; however, an overall conclusion cannot be derived here as no alternative has the most favourable results for all the impact categories quantified. The viable alternatives proposed to the real scenario involve improvements, but also worsened consequences.

Concerning eutrophication, the beneficial impact due to fertilisers avoided when sludge is applied to the land is lost as no nutrients are recovered when the other options are carried out. However, this favourable result is on a par with a significant negative aspect: the toxic impacts associated with land application are strongly reduced when considering either scenario 1 (incineration) or 2 (pyrolysis).

Regarding Global Warming (GWP), it is necessary to mention that, as was indicated in the tables, an important part of the CO_2 involved in the inventories is biogenic as it comes from the complete degradation of organic matter. This CO_2 was considered not to contribute to the climatic change effect and it was subtracted from the global warming balance at each scenario. In **Fig. 5**, the values before and after the subtraction of those burdens are presented.

A similar figure was offered by Houllion and Jolliet [12], and although the sludge treatments considered are not the same, the values presented are similar. For instance, anaerobic digestion seems to be a good option for stabilising the sludge previous to land application, as less greenhouse gas emission is produced.

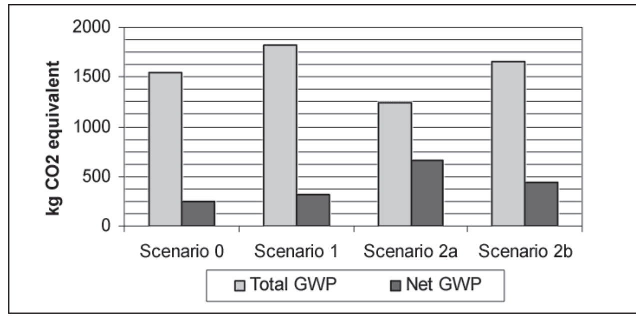

Fig. 5: Global warming balance of the scenarios under study. Values are presented per FU

As far as Acidification (AP) is concerned, scenario 1 stands for the most environmentally-friendly option showing a reduction of the impact caused by the actual scenario. The reason for this fact is the severe gas emission control system implemented that makes it possible to release very few contaminants into the environment together with a small amount of energy required as an external demand.

Related to toxicity potentials, the emissions of heavy metals present in the sludge are behind the high values obtained. However, it must be noticed that the most adverse case was applied and, consequently, the numbers stand for the maximum possible values. More research is required in order to establish the precise amount of heavy metals that reach the soil and are likely to go up the food chain or to contaminant the ground water. It is known that different metals behave entirely differently in a certain soil as well as does a particular metal in different soils [38], and there is no point in establishing a figure with no real data to support it.

In any case, it should be indicated that, for some reason, the concentration of lead (Pb) in the sludge under study is superior to the normal values in the bibliography (see Table 2); and, in order to compensate for the probable overestimation, a sensitivity analysis was performed with different Pb concentrations in the sludge (**Fig. 6**):

- Real concentration of Pb, that is 334 mg per kg of dry matter
- Hypothetical concentration of 221 mg of Pb per kg of dry matter, the upper value for the EU range [24]
- Hypothetical concentration of 117 mg of Pb per kg of dry matter, the average value for the EU range [24]

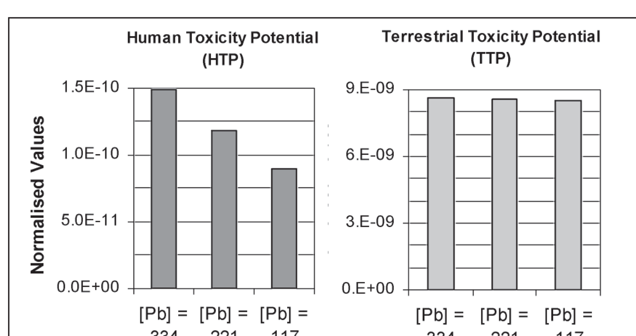

Fig. 6: Sensitivity analysis: Influence of the Pb concentration on toxicity potentials. Values are presented per FU

As the figure suggests, there is a great dependence of Pb on the human toxicity potential. On the contrary, no significant alteration is shown at terrestrial toxicity potential. Even then, the values are still higher that those calculated for the alternative scenarios.

Qualitative considerations regarding the environmental impact of sludge processes. The use of sludge in agriculture involves several contested issues that affect many people and supporters and opponents have defended their position for a long time; in fact, as a consequence of the lengthy debate, it appears to be in deadlock [39].

Apart from heavy metals, sludge contains pathogens and organic pollutants that can be transferred to the environment or to humans. This aspect has been left beyond the scope of the study, mainly due to two reasons:

- At Scenario 0, anaerobic digestion is responsible for the stabilisation of the sludge; however, this treatment cannot provide a 100% reduction of pathogens and viruses, and these harmful substances may be prone to reaching the environment. Even when the 3rd draft of the 'Working document on sludge' [2] is still waiting to be accepted, some of the aspects that are considered there should be taken into consideration when sludge treatments are studied. According to this document, land application of sludge will always be possible after advanced treatment (please see Annex 1 on the document mentioned). In the WWTP under study, mesophilic anaerobic digestion is carried out that is not enough for an advanced treatment: a thermophilic anaerobic digestion (53°C for at least 20 h) or thermal treatment of liquid sludge (70ºC for a minimum of 30 min) followed by mesophilic anaerobic digestion will be the modifications required. Both options imply a higher energetic consumption that would penalise the environmental performance of Scenario 0.
- The sludge characterisation used here was obtained by following the procedure established by the Spanish legislation [26], where the following parameters are determined: pH, dry matter, organic matter, nitrogen, phosphorous according to standard methods and heavy metals such as cadmium, copper, nickel, lead, zinc, mercury and chromium, by atomic-absorption spectroscopy. No information regarding organic compounds existent in the sludge was available and, consequently, they were not included in the study.

In spite of these comments, it is clear that this aspect should be included when an environmental evaluation is performed and, in this sense, other tools such as risk assessment would be more appropriate for the analysis [13,40].

5 Conclusions

Sewage sludge is generated as an unavoidable waste product from the treatment of wastewater. Since its disposal to agriculture and landfill is more and more carefully controlled, alternative, thermal disposal routes arise as possible procedures.

During the last few years, several opinions have been given in favour of land application, incineration or pyrolysis, but also many voices have spoken out against each of them. To obtain general conclusions for an overall comparison of different post-treatment of urban wastewater sludge is not easy as many contradictory aspects take place. The most effective utilisation of sewage sludge implies both energy and material re-use, but this is not always possible.

Agricultural utilisation is today being put under more and more pressure due to the awareness of toxic compounds. Here, the most adverse case (that is to say, the total amount of heavy metals is supposed to be released from the sludge and reach the environment) was applied to consider the most negative impact due to sludge spreading in agricultural soils; so more research is required in order to establish the precise amount of heavy metals that is effectively uptaken by the plants and crops as well as the amount that is transferred to another phase as a leachate.

Thermal processes have been presented as a good option to recover energy from the sludge; however, more efforts are needed to improve the valuable, viable products, as nutrients are lost during the process. Tar and char, co-products from pyrolysis, are good examples that were evaluated here, while the recycling of bottom ashes from sludge incineration or the manufacture of ceramic materials from sludge are other options that are planned to be studied in the near future.

As a general conclusion and as was emphasized by Campbell [41], the most important criterion in the selection of any sludge management strategy is that the solution must be appropriate to the conditions of the site in question, therefore, there is no universal solution to the problem of sludge management and its long-term sustainability. Nevertheless, we think that land application of digested sludge is an acceptable option; probably not the best, but at least a good one, for sludge treatment as long as efforts are focused on the minimisation of the heavy metal content in the final cake.

Here, only an environmental perspective was taken into account. However, the search for the most sustainable alternative for sludge treatment has to include a social evaluation and economic analysis as well. The three vectors must be considered if sustainability is aimed for.

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